



# Article A New Project for a Much More Diverse Moroccan Strategic Version: The Generalization of Solar Water Heater

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**Abstract:** This paper presents a strategical project for the new version of the Moroccan energy policy. It highlights the technology of solar water heaters (SWH), studying energy, economic and environmental gains of SWH generalization to satisfy the total resident need proposing a new strategic version diversified in terms of adopted technologies (more than green electricity). A detailed analysis of thermal performances and economic profitability of direct thermosyphon solar water heaters (TSWH) for residential requirements in Morocco. The optimum design parameters were defined and investigated using the dynamic TRNSYS simulation program. The optimum system was simulated under the six climatic conditions of Morocco in order to assess the related performances in terms of the collector efficiency and solar fraction. The major finding of this work is that large-scale integration of TSWH into Moroccan residences could provide up to 70% of thermal energy loads. An economic study was also developed to predict the life-cycle savings generated by the generalization of this technology in Morocco for all residential building's categories. Approximately 1250 million USD as national saving on the total energy bill can be achieved. The environmental effects were also assessed to achieve the aims of this work and to evaluate the  $CO_2$  emissions avoided due to this environmentally friendly solution.

**Keywords:** solar hot waters; thermosyphon; thermal performance; Morocco; economic outcomes; CO<sub>2</sub> environmental assessment

# 1. Introduction

Sun is an abundant alternative source of clean, renewable, and sustainable energy [1]. However, it was found that solar energy remains until now not fully exploited because of the high initial cost of solar thermal technologies [2], particularly in Morocco, a member country of the Middle East and North Africa (MENA) and considered as a case study in this work. In fact, one of the most valuable new policies is the integration of solar energy in the building sector to satisfy the needs of domestic hot water in Morocco, principally through solar thermal technologies. Indeed, thermosyphon solar water heaters (TSWH) can reduce intensively the consumption of butane gas, develop the market of solar energy in Morocco, and as a result widen the overall area of installed collectors. The use of such technologies can also participate to reach national targets related to energy efficiency (EE) in the building sector [3]. Finally, solar thermal heaters can enhance the safety aspect during the utilization phase by avoiding the phenomenon of fatal accidents due to the exhaust of butane gas which was estimated at 60 deaths per year according to Gergaud et al. [4].

TSWH has become the most used technology around the world to heat water. It is defined as a passive solar technology based on natural convection, without the necessity



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of using mechanical or electrical power to pump and circulate the fluid neither its control. Fluid's circulation is the result of the density difference caused by the solar fluid heating considered as a driving force. Thermosyphon is described as the oldest technology which was introduced into the world market. Its performance is equal to the active systems and remains efficient in some cases. Hence, it can be concluded that the thermosyphon technology is the simpler system that could be designed [5].

The performance of solar water heaters has been developed and assessed theoretically and experimentally in several works. For example, Michaelides et al. [6] studied, different configurations of solar water heating systems, especially the under meteorological and socio-economic conditions of Cyprus, using different load profiles where the results showed that the solar fraction balanced between 89 and 63% depending on the consumption pattern studied (low and high). Moreover, Carlsson et al. [7] studied the thermosyphon system by replacing the traditional materials with polymeric ones, in order to compare the thermal, and financial performances. It was found that the total energy costs could be reduced considerably using the polymeric material. Further detailed analyses on Thermosyphon performances were also investigated by Kalogirou et al. [8]. Authors studied the performance of a TSWH considering a series arrangement and formulated a novel heat exchanger model to evaluate the effects of many parameters such as the inclination angle, coupling geometries and aspect ratio on the global performance. The most influential parameter was found to be the aspect ratio which affected to temperature and efficiency according a linear trend [9,10].

Many researchers have focused on innovative techniques to improve the efficiency of TSWH; Vasiliev [11] discussed using of new two-phase termosyphons technologies with advanced performances in order to study identical long construction with different working fluids, to examine the thermal performances especial the resistance which can be lowed using the vapordynamic thermosiphon (VDT) thernosyphons and polymeric loop two-phase under different parameters such us the inclination. The innovation continuous to appear in many other works, such as Piotr Felinski's [12] study which applies the phase change material (PCM) and the paraffin in evacuated tube collectors for domestic hot water application, to evaluate the effect of this materials and thermal performance. The results showed that the use of evacuated tube collector (ETC) with PCM and paraffin allowed height water temperatures and improved solar fractions during the peak loads and the periods of lowest solar radiation intensities under the typical meteorological year conditions, compared to the conventional types. While the conventional ETC showed in several works right performances in terms of water temperatures, yields, energy and exergy efficiencies for many applications; thermosyphonic and forced models [13–15]. Koffi et al. [16] studied theoretically and experimentally a TSWH with an internal exchanger in order to assess the effect of some operating parameters on the outlet temperature and collector thermal efficiency. This study was investigated for Ivory Coast climatic conditions in 2014. Zerrouki et al. [17] studied the outlook for the use of a thermosyphon system manufactured in Algeria to predict its efficiency under the Algerien climatic conditions. Another study, with the same purpose was carried out under clear nights conditions and using the thermosyphon system with at-plat collectors by Runsheng Tang et al. [18]. Many other works were developed recently to study the general performances TSWH. For instance, Zeghib et al. [19] in Algeria presented a new theoretical simulation model, to predict the performance and the system behaviors under a thermosiphonic operation. The model was carried out using a flat plat collector with an area of 2 m<sup>2</sup> for a volume of 200 L. Consequently, the theoretical analysis results height heat energy output, and satisfying efficiencies of collector and auxiliary heater improved by the good stratification of the model designed compared to the fully mixed conventional models. Vieira et al. [20] performed a multiparametric study of SWH system under the climatic conditions of Brisbane in Australia, using EnergyPlus 8.6 software. The model's calculations and analysis showed that the split systems perform better than thermosiphon system in terms of service level and energy efficiency. Another parametric study based on the load profiles influence was carried out

by ERICH HAHNE [21]. The analysis was performed using a solar combisystem using a storage tank with an internal thermosiphonally driven discharge unit, operating under realistic profiles of 1-min scales and a constant total yearly demand. The results showed that the load profile have a severe influence on the system performances, this is explained by the significant role of the duration and the flow rates of DHW (Domestic Hot Water) on the stratification and temperatures. S. Fung et al. [22] presented two existing systems in his work, drain water heat recovery (DWHR) system and two solar domestic water heaters (SDWH) intended for two houses, the study aims to evaluate the performances and the recovery potential of systems, using two collector technologies; flat plat collector and ETC as a result the DWHR present an effectiveness of 50%, and the productivity of sensors was evaluated. Several works were investigated to study other types of solar water heaters. The analysis of Hobbi et al. [23] could be cited as example. Authors simulated and optimized a forced circulation using the flat plat collectors for residential SWH application in Montréal Canada, the study aims to show the importance of solar energy which could provide between 83–97% of the hot water demand in summer. The aim is to improve the efficiency of systems integrated in buildings, in order to reach economical and efficient buildings. Something that can be achieved with a multitude of actions [24,25]. Thermosyphon effect has several other technological uses, Chen and Yang [26] solve the efficiency problem for concentrating solar cells due to their height temperature, by the integration of the loop thermosyphon in the heat dissipation system. Different fluid for the operating thermosyphon loop were used. The results of theoretical and experimental analyses showed that the acetone is better than water and ethanol in term of heat transfer. Solomon et al. [27] focused on the closed system presenting the comparison between the two phase closed thermosyphon (TPCT), porous copper coating and the uncoated, the results showed that difference in heat transfer coefficients between the two cases at an angle of 45° is 44% at a heat flux of 10 kW.m<sup>-2</sup>. Furthermore, more the copper coating is thin more the wall temperature of the evaporator is significant and the heat transfer coefficient is increased, which makes the thin coating a suitable for cooling high-density power. Kousksou et al. [28] presented a numerical study which is concerned with the integration of phase change materials (PCMs) in solar-based domestic hot water (DHW) systems, so as to enhance its overall performances.

In the literature, many works join to the technical study an economic analysis to present a significant result, especially for the strategically and policies works [29]. Recent economic studies regarding solar water heaters integration were published. The technoeconomic benefits and reliabilities of solar water heaters using the Monte Carlo analysis were estimated by Rezvani et al. [30]. They focused on a product range manufactured by a local company in Australia. Sokka et al. [31] focused on the environmental impacts of solar energy. Greenhouse gas emissions and mitigation of climate change reduction were studied which is the main aim of the global climate policy. Bouhal et al. [32] investigated the impact of collector technology and load profile on the fractional savings of solar domestic water heaters under various climatic conditions in Morocco. While an energy analysis of solar domestic heating water systems was conducted by Allouhi et al. [33].

In the present work, the preliminary choice of the technology to be integrated into the Moroccan context was made based on the results of the different systems studied in the work exhibited in the literature review previously mentioned, the particularity of this study is to integrate the Moroccan climate context, economic and social in the choice and the technical elaboration of the adapted model in order to present a realistic study combining the technology and the current conjuncture of Morocco as part of an African area and fertile ground of the generalization project. For Morocco, solar energy is a crucial economic issue in coherence with the choice of sustainable development and the related energy policy, which aims promoting renewable energies to meet 20% of the country's domestic energy needs, improving energy efficiency to achieve 12% reduction by 2020. Solar energy utilization is expected to play a pivotal role in environment protection and social development [34,35]. This orientation leaded many actions, laws and projects to integrate green solutions precisely the solar within different sectors [36], especially the building sector which presents 20.4% of the national total energy consumption [37], this sector is characterized, firstly by a quick development because of fast population growth and an increasing urbanization rate [38,39].

Through this study, large-scale integration of TSWH into various types of buildings in Morocco is discussed energetically and financially based on climatic data of six different climatic zones of Morocco [35]. The performance indicators describing the system in this work are the solar fraction and collector efficiency. The simulation outputs were then used to develop the economic study, which aims to quantify the possible financial gains of generalizing the utilization of TSWH in the domestic sector of Morocco. This assessment was made by comparing the solar system with conventional gas heaters which is the most used heating option in the country. Two scenarios of subsidies elimination for conventional energy sources are discussed and the national potentiality of  $CO_2$  emissions reduction resulting from generalizing this kind of water heaters is assessed.

#### 2. Moroccan Context Related to the Study Goal

In 2008, Morocco faced many challenges. An energy system marked by an extreme dependence on the outside world, a predominance of petroleum products and hydrocarbons in general, sustained growth in demand, increased rural electrification, and high price and price volatility. Despite the relevance of the 2009 strategy's vision and the break it has initiated, with the desire to increase the share of renewable energy. The strategy made it possible to secure the supply, to initiate the liberalization of the electricity market and position Morocco at the forefront of the climate agenda, however this first version of Moroccan energy strategy have several lacks and brakes, such as the focus on the photovoltaique renewable technology; that requires the adoption of new strategic orientations.

This energy strategy adopted in 2009 has consolidated many achievements and must now be revisited. It is necessary to focus on exploiting this deposit to position the Morocco as the energy transition leader. The exploitation of the Moroccan potential conducted in an integrated and inclusive way should benefit the citizen, the economy, and the State.

Many actions will be taken in the new energy strategy version such as training, research, development and innovation: invest more in human capital to build a pool of business skills and networks of researchers and engineers engaged in a global dynamic, both national and regional. Further, we should promote the initiatives undertaken by the ecosystem approach of "Institut de Recherche en Energie Solaire et Energies Nouvelles" (IRESEN) and its partners (universities). Besides the diversification of the energy technologies adopted (more than photovoltaiques and electricity production) is one of the necessaries actions. In this sense, Morocco lunched several projects to support the solar thermal technologies and specially for residential uses. The PROMASOL (programme de développement du marché marocain des chauffe-eau solaires) project was one of the first lunched since the first version which aims to develop the Moroccan solar thermal market, but it didn't make significant results. For this reason, Morocco lunched a new project about solar water heaters which aims to present a new Moroccan SWH with an accessible price and adapted technology to the economic and the climatic context.

For that, an overview of the solar thermal market in morocco is necessary to introduce the present study, and situate this project proposition of (generalization of SWH).

Morocco's equipment level has always remained around four times lower than the global average; this means, notably, its equipment level remained parallel to the world's equipment level. Despite its good sunshine, Morocco is still not among the countries installed capacity in 2018 but, Figure 1 shows that it is listed in the third group of countries (total of five), having between 20 and 70 m<sup>2</sup> for 1000 habitants [40].



Figure 1. Evolution of the total installed area per inhabitant in Morocco compared to the world.

Morocco's share of installed solar thermal capacity is low but remained stable for three decades as showed in Figure 2, around 0.10%. This means that the growth in m<sup>2</sup> installed in Morocco has been parallel to the world trend [41].



Figure 2. Evolution of the accumulation of the installed area in Morocco (% from the total in world).

On a 30-year scale, Figure 3 shows that: prices in Dh/m<sup>2</sup>, cost insurance and freight (CIF, blue diamonds in Figure 3), fluctuated by 15% (vertical blue bars in Figure 3) around a prolonged decrease of nearly 0.34% per year (decreasing blue curve in Figure 3). Solar thermal is no longer in the maturation phase and no longer undergoes a "learning curve." Thus, prices would have lost only 5 to 6% in 30 years, which is low but appreciable considering inflation and increased purchasing power. The thermal energy produced by solar collectors has always been more profitable than that produced by grid electricity. Even very modest, this drop in prices combined with the rise in electricity prices has made this profitability even more attractive. Although "fair play," this competitiveness goes unnoticed because of the formidable competitor of thermal energy produced by butane gas, which is heavily subsidized. Indeed, the withdrawal of the compensation 12 kg bottle would place its price around 120–140 MAD (Moroccan dirham) and not 40 MAD. Because of this, in Morocco, a solar water heater depreciates in 10 years against its butane gas competitor, regardless of the advantages related to comfort and safety of use.

The installation of solar thermal systems would have contributed to creating a few dozen jobs until around 2007. The number of jobs created amounted to a few hundred until around 2018 and seemed to stagnate around a little over 200 [42].

The annual demand has almost multiplied by 15 in 25 years or average growth of nearly 11% per year, which is not very fast compared to the growth of other renewable energies such as photovoltaics [43]. It is even surprising that the demand is maintained over such a long period despite the harsh competition of butane gas.



Figure 3. Evolution of the unit wholesale price of thermal collectors (MAD per m<sup>2</sup>) [42].

Domestic Solar water heaters (DSWH) have always dominated the sales of the market as described in Figure 4, making a significant turnover presented in Figure 5. As showed in Figure 6 they tend to dominate it more and more to exceed 80% after having fallen around 75% in the middle of the decade 2000–2010, probably under the PROMASOL Program's impetus, which was led by AMEE (Agency for Control and Energy Efficiency).



**Figure 4.** Evolution of the solar thermal collector's cumulative area installed annually in Morocco vs. the national market (imported: installed and not installed).



Figure 5. Turnover evolution (solar thermal Moroccan market) for 3500 MAD/m<sup>2</sup>. [42].



Figure 6. Domestic solar water heaters sales in Morocco.

All the elements presented describe the Moroccan market as a fertile ground for the insertion of this technology and popularizing it. This study assesses the positive impacts of the integration and generalization of this technology at the national level in order to improve the previously presented results further and generate a significant share of the economic and environmental gains not only by the production of green electricity but also by the production of domestic hot water and the coverage of all residential needs by solar.

# 3. Methodology

The TSWH is simulated using the TRNSYS (transient system simulation tool) program. The main operating and design parameters were introduced; the design parameters include general specifications of the used thermal collector, storage tank and auxiliary system. Weather data files for the various Moroccan climatic zones are then integrated into the simulation process. A realistic load profile is as well considered for accurate prediction of thermal loads and system performances. Based on the hourly output data, namely water outlet in the solar collector and temperature inside the tank, energetic performance indexes were built. These indices are the monthly solar fractions and collector thermal efficiencies.

Based on the evaluated useful energy produced by the TSWH and the total thermal loads required, a large-scale economic study is developed to examine the potential of generalizing these systems into the Moroccan residential sector. This evaluation is based on a comparison of cumulative energy savings generated by switching from the conventional gas heaters to TSWH. Finally, it was possible to estimate the overall reductions in CO<sub>2</sub> emissions.

The assessment is believed to be sufficiently accurate as it follows a rational methodology for quantifying the full-scale economic impact of generalizing these solar systems. First of all, it was necessary to evaluate the number of capita per climatic zone, this parameter is not yet available, it is available only in a regional database according to the High Commission of Plans. Therefore, it was essential to convert the available regional data to comply with the climatic zoning. A schematic diagram of the followed methodology is shown in Figure 7.



Figure 7. Methodology.

# 4. Simulation Process

# 4.1. Examined Configuration

The TSWH consists of a flat plate collector (FPC) connected to an auxiliary heater integrated inside a horizontal tank as presented in Figure 8. For this system, water flows through the system when warm water rises as cooler water sinks without the need for a circulation pump. The FPC collector is installed below the storage tank so that warm water will rise into the tank by the thermosiphon effect, its principle operates on the heated water's characteristic, which becomes lighter than the cold water, ascends to the horizontal tank, replaces the cold water, which, heavier, descends downwards and passes through the solar panel.



Figure 8. Thermosyphon system schematic.

First of all, optimum tilt angles per each zone were determined. These angles are summarized in Table 1.

Table 1. Optimal tilt angle.

| Zone          | Agadir       | Marrakech    | Errachidia   | FES          | Ifrane       | Tangier |
|---------------|--------------|--------------|--------------|--------------|--------------|---------|
| Optimal angle | $30^{\circ}$ | $31^{\circ}$ | $31^{\circ}$ | $32^{\circ}$ | $30^{\circ}$ | 32°     |

Moreover, the technical characteristics of the solar collector used during the simulations under TRNSYS are presented in the Table 2.

Table 2. Thermosyphon solar water heater characteristics.

| Parameter                           | Value | Unit                                     |
|-------------------------------------|-------|--|
| Collector area                      | 2.2   | m <sup>2</sup>                           |
| Intercept efficiency                | 0.74  | -  |
| Efficiency slope                    | 12.33 | $kJ\cdot h^{-1}\cdot m^{-2}\cdot K^{-1}$ |
| Tested flow rate                    | 30    | $kg\cdot h^{-1}\cdot m^{-2}$             |
| Collector slope                     | 30-32 | °  |
| Number of parallel collector risers | 10    | -  |
| Riser diameter                      | 0.2   | mm                                       |
| Header diameter                     | 0.2   | mm                                       |
| Header length                       | 1.0   | mm                                       |

| Parameter                               | Value      | Unit                                     |
|---|------------|--|
| Collector inlet to outlet distance      | 1.273      | mm                                       |
| Collector inlet to tank outlet distance | 0.25       | mm                                       |
| Collector inlet diameter                | 0.2        | mm                                       |
| Length of collector inlet               | 1.0        | mm                                       |
| Collector outlet diameter               | 0.2        | mm                                       |
| Length of collector outlet              | 1.0        | mm                                       |
| Outlet pipe losses coefficient          | 15         | $kJ\cdot h^{-1}\cdot m^{-2}\cdot K^{-1}$ |
| Tank volume                             | 202        | L  |
| Fluid specific heat                     | 4.190      | $kJ\cdot kg^{-1}\cdot K^{-1}$            |
| Fluid density                           | 1000.0     | kg·m <sup>−3</sup>                       |
| Tank configuration                      | HORIZENTAL | -  |
| Maximum heating rate                    | 2          | kW                                       |
| Maximum pressure                        | 8          | Bars                                     |
| Thermal losses of the tank              | 1.8        | $kW \cdot h^{-1} \cdot m^{-2}$           |
| Capacity of solar circuit               | 5          | L  |

Table 2. Cont.

### 4.2. Climatic Data and Geographical Specification

The Moroccan climatic conditions used to assess the thermal performance of the thermosyphon are presented in Table 3 and Figure 9. This new climatic zoning is established by the Moroccan Agency of Energy Efficiency (AMEE).

Because the Moroccan climate exhibits a great variability according to the geographical zone, it was necessary to perform a segmentation of the whole territory into areas with similar overall meteorological specifications. Accordingly, the Moroccan Agency of Energy Efficiency (AMEE) [44], proposed a climatic fragmentation of Morocco according to six climates, each climate is evidenced by a representative city. Table 2 shows general information about these zones. In addition, the main meteorological data (i.e., monthly average ambient temperature and solar irradiations) affecting the energetic performance of TSWHs is displayed in Figure 9. One can observe that the climate presents a remarkable variety which is expected to influence greatly the overall thermal behavior and performance of TSWHs.

#### 4.3. Load Profile

The distribution of the hourly hot water consumption is affected by different factors. It varies according to the seasons, days, or the habits of each considered Moroccan family. Various hot water load profile has been studied on the literature review such as the constant, the early morning, the late morning, rand, or the late afternoon profiles. For the present study, the consumption of 202 L per day is described according to the realistic load profile presented in the Figure 10.

| Climatic Zone | Representative City | Altitude (m) | Coordinates      | Climate                   | Temperature °C |
|---------------|---------------------|--------------|------------------|---------------------------|----------------|
| Z1            | AGADIR              | 31           | 30°25′ N 9°36′ W | Subtropical-semiarid      | 14.3-23.2      |
| Z2            | TANGER              | 20           | 35°46′ N 5°48′ W | Mediterranean hot         | 12.6-24.2      |
| Z3            | FES                 | 403          | 34°03′ N 4°58′ W | Mediterranean/continental | 9.6-26         |
| Z4            | IFRANE              | 2019         | 33°32′ N 4°58′ W | Humid temperate climate   | 6.2-25.4       |
| Z5            | MARRAKECH           | 457          | 31°37′ N 8°00′ W | Semiarid                  | 12.4–28        |
| Z6            | ER-RACHIDIA         | 141          | 31°55′ N 4°25′ W | Hot desert                | 9.1–33.2       |

Table 3. General Information of the climatic zones under investigation.



Figure 9. Weather data.



Figure 10. Realistic Moroccan load profile for hot water consumption.

#### 4.4. Physical Modeling

The type 45 operates according to a mathematical model [45] which presents the various phenomena describing its operation. The Bernoulli formula can be applied to define the pressure drop in the thermosyphon system's nodes (Equation (1)):

$$\Delta P_i = \rho_i g \Delta h_i + \rho_i g h_{Li} \tag{1}$$

where (*i*) is the index of the node,  $\Delta h_i$  the height of the ith node,  $\rho$  is the density,  $h_{Li}$  is the frictional head loss in the piping, and *g* is the gravitational constant.

The flow rate on the thermosyphon system must be involved in order to satisfy the conditions describing the total pressure differences, which are determined using the equation above at any time by the next expression (2):

$$\sum_{i=1}^{i=N} \rho_i \Delta h_i = \sum_{i=1}^{i=N} \rho_i h_{Li} \tag{2}$$

Many types of losses are present in the system; the most important one is the frictional head loses especially on the pipes, and the equation below describes this type of losses (3):

$$H_p = \frac{fLv^2}{2d} + \frac{Kv^2}{2} \tag{3}$$

The parameter F is the friction factor, determined according to the value of the Reynolds coefficient  $R_e$  which describe the nature of the flow and corrected to take in account the frictions on the connecting parts of pipes. The head loses pipe varies according to the position and the conditions in the system, these specifications are taken into account

by the coefficient *K*, e.g., loses due to different types of bends, the parts of the tank which are connected to the collector.

The thermal performance of collector is modeled according to the Hottel–Whillier equation. Many parameters describe the system: the equation bellow (4) defines the  $F'U_L$  parameter which is calculated by the  $F_RU_L$  and G parameters determined on the test conditions.

$$F'U_L = -G_{test} C_P \ln\left(1 - \frac{F_R U_L}{G_{test} C_p}\right)$$
(4)

For the collector the temperature in the  $K_{\text{th}}$  node is calculated by the next expression (5):

$$T_{ck} = T_a + \frac{I_T F_{R(\tau\alpha)}}{F_R U_L} + \left(T_{ci} - T_a - \frac{I_T F_{R(\tau\alpha)}}{F_R U_L}\right) \exp\left[\frac{F' U_L}{GC_p} \frac{(k - 1/2)}{N_x}\right]$$
(5)

where  $N_x$  is the number of nodes over which the size of the collector deviates to obtain the weight of the fluid in the collector.

The changes in the fluid heat transfer coefficient results in F' and  $U_L$  which are considered negligible. The combination of the intercept efficiency at normal incidence  $F_R$  ( $\tau \alpha$ )<sub>*n*</sub>, and the incidence angle modifier (IAM).

 $((\tau \alpha))_n$  allows us to calculate the parameter  $F_{R(\tau \alpha)}$  (6):

$$\frac{(\tau\alpha)}{(\tau\alpha)_n} = \frac{I_{bT}\frac{(\tau\alpha)_b}{(\tau\alpha)_n} + I_d\frac{1+\cos\beta}{2}\frac{(\tau\alpha)_s}{(\tau\alpha)_n} + I_g\frac{1+\cos\beta}{2}\frac{(\tau\alpha)_g}{(\tau\alpha)_n}}{I_T}$$
(6)

where the incidence angle modifiers for ground and sky diffuse radiation is calculated using the next Equation (7):

$$\frac{(\tau\alpha)_b}{(\tau\alpha)_n} = 1 - b_0 \left(\frac{1}{\cos\theta} - 1\right) \tag{7}$$

The overall useful energy collected is determined using the Equations (8) and (9):

$$Q_u = r A_c \left( F_{R(\tau \alpha)} I_T - F_R U_L(T_{ci} - T_a) \right)$$
(8)

$$r = \frac{F_{R(use)}}{F_{R(test)}} = \frac{G\left(1 - \exp\left(-\frac{F'U_L}{GC_P}\right)\right)}{G_{test}\left(1 - \exp\left(-\frac{F'U_L}{G_{test}C_P}\right)\right)}$$
(9)

The outlet temperature from the flat plat collector is finally deduced as (10):

$$T_{\rm CO} = \frac{Q_u}{\dot{m}C_p} + T_{\rm Ci} \tag{10}$$

The thermosyphon diagram executed under TRNSYS program is shown in Figure 11. The different module's types used in this study are presented as follows:

- Weather data (TYPE109-TMY2) this component reads meteorological data generated by meteonorm software and supply them in the TMY2 format. It calculates the necessary solar radiation for the calculation of TRNSYS software at any surface tilt.
- Differential controller for temperature (TYPE 2). This component monitors and controls the average temperature of the tank, to control the operation of the auxiliary electric heater.
- The general forcing function (TYPE 14) from TRNSYS library, this component describes and characterizes the hourly load profile corresponding to 202 L/day of hot water demand.



Figure 11. Thermosyphon diagram executed under the TRNSYS program.

#### 4.5. Performance Indices

#### 4.5.1. Collector Efficiency

The collector efficiency describes the ratio of the total useful energy gain to the solar energy absorbed by the collector. It is calculated using the equation below (11):

$$E_{coll} = Q_{ucoll} / (A_c \ I_{coll}) \tag{11}$$

 $Q_{ucoll}$  is the energy rate from heat source, and  $I_{coll}$  is the total radiation on the tilted surface.

# 4.5.2. Solar Fraction

The solar fraction  $F_{sol}$  represents the solar energy available to meet the needs. It presents a clear contribution indication of the solar system in meeting the thermal load. The solar fraction is calculated using the equation below (12):

$$F_{sol} = 1 - \left(Q_{aux}/Q_{DHW}\right) \tag{12}$$

where  $Q_{DHW}$  is the energy rate delivered to the load describing the necessary energy to meet all domestic hot water needs, and  $Q_{aux}$  is the auxiliary energy. It is important to state that the solar fraction is evaluated on a monthly basis.

# 5. Model Validation

The developed model was simulated with firstly the meteorological data of Cyprus in order to carry out a comparison with the study performed by Michaelides et al. study [6]. A typical meteorological year (TMY) for Nosica was built for this end.

The system simulation was lunched for similar conditions as indicated in [6]. Table 4 shows the technical specifications of the studied TSWH while Tables 4 and 5 indicates the general assumptions concerning technical parameters of validation case, the load profile and water consumption.

 Table 4. Consumption profile of the validation study.

| Profile Code | Daily HW Consumption L/Person | Temperature (°C) | Pattern     |
|--------------|-------------------------------|------------------|-------------|
| DOM          | 30                            | 50               | Michaelides |

| Parameter         | Value   |
|-------------------|---|
| Ac                | 2.72 m <sup>2</sup>   |
| $F_R$             | 0.791   |
| $F_R U_L$         | $24 \text{ kJ} \cdot \text{h}^{-1} \cdot \text{m}^{-2} \cdot \text{k}^{-1}$ |
| G <sub>test</sub> | 96 kg·h <sup>-1</sup> ·m <sup>-2</sup>                                      |
| β                 | $40^{\circ}$  |
| $N_R$             | 20  |
| $D_r$             | 15 mm   |
| $d_i, d_o$        | 22 mm, 22 mm  |
| $H_c$             | 1000 mm   |
| $H_O$             | 1150 mm   |
| $H_r$             | 250 mm  |
| $H_a$             | 300 mm  |
| $H_{th}$          | 370 mm  |
| $L_i$ , $L_o$     | 2000 mm, 520 mm   |
| $U_{api}$         | $5.1  \text{kJ} \cdot \text{h}^{-1} \cdot \text{k}^{-1}$                    |
| $U_{APo}$         | $5.1  \text{kJ} \cdot \text{h}^{-1} \cdot \text{k}^{-1}$                    |
| V                 | 162 L   |
| $(UA)_s$          | $6.45 \text{ kJ} \cdot \text{h}^{-1} \cdot \text{k}^{-1}$                   |
| Qaux              | 3 kW  |

| Table 5. Technical parameters of the validation study. |
|--|
|--|

Figure 12 presents a comparison between monthly solar fractions of the TSWH investigated by Michaelides et al. study [6] and those predicted by the introduced TRNSYS model.



Figure 12. Solar fraction of Michaelides study versus validation study.

The average relative error is about 5%, which is an acceptable value. The deviation between the results can be attributed to the update in climatic conditions caused when using the Meteonorm database that corresponded to the period 1986–1992 for the study of Michaelides et al. [6] while the prepared metorological data file used in our calculations corresponds to the period 1991–2010.

#### 6. Results and Discussion

#### 6.1. Energetic Evaluation

As presented in Figure 13a, the thermosyphon system performs differently in the six cases. The average solar fraction ranges between 46% to 71%, and the maximum solar fraction value was noticed in Errachidia 71%. This result is explained by the importance of solar irradiations in this zone. The annual average solar fraction is about 69% in the first zone represented by Agadir which is a sunny coastal zone. It is in general the most favorable zone for this system, especially in winter.



Figure 13. (a) Solar fraction. (b) Collector's efficiency.

Tangier (Zone 2) and Marrakech (Zone 5) exhibit approximately the same solar fraction variation, but (Zone 5) has a higher annual average value of 66% versus 61% in (Zone 2). This difference is due to the favorable conditions of Marrakech which is considered as one of the sunniest areas in Morocco. Zone 3 presents a total annual average solar fraction of 52%, which is lower compared to the previously discussed sites. This result can be explained by the fact that Fez is characterized by a Mediterranean climate, dominated by continental and Atlantic effects, which accounts for the remarkable fall of the solar fraction to 17.4% during the coldest month of winter. Finally, the coldest zone, Ifrane has an averaged solar fraction value of only 46%. It is concluded that Ifrane's weather is the most unfavorable climate for installing solar TSWHs because Ifrane remains the coldest zone in Morocco with an average annual temperature of 10.8 °C. In addition, one can observe that most of the hot water requirements in the Moroccan zones, previously cited, are totally satisfied during the sunniest three months of the year (July, August, and September) with a solar fraction achieving 100%.

Figure 13b presents the dynamic behavior of the collector efficiency for the six zones. The most favorable zone, where the collector performs with high efficiency is Zone 6 represented by Errachidia, with a maximum value of 86% in July, and an average annual value of 74%. The collector operates in Agadir with 70% of efficiency, in Marrakech with 66%, Fez and Tangier with 54% and 59% respectively and finally in Ifrane with 51%. These results confirm the explanations previously presented for solar fraction. In fact, when the thermal efficiency of the collector is maximized, the useful thermal energy transmitted to the working fluid is as well maximized and thus less auxiliary energy will be required.

#### 6.2. Economic Assessment

This section aims to assess the total financial gains generated by the integration and the generalization of solar water heaters in Morocco into the residential sector, according to the six climatic zones and for different house's types. The solar system will be compared to a reference system which is the conventional gas boiler according to two scenarios:

- 1. The first scenario takes into account the state subsidies on gas, which presents a purchasing power support of households. In this case, the consumer benefits on each bottle of gas that purchased a reduction of 67% on its price.
- 2. The second scenario does not consider the subsidies.

The number of thermosyphon systems required to be installed was determined according to the situation of the building in Morocco. The number of houses counted on 2014 is 5.8 million, distributed as follow: occupied houses, secondary, vacant and professional use houses as presented in Table 6.

Table 6. Distribution of houses in Morocco according to the 2014 census.

| Туре                       | Percentage |
|----------------------------|------------|
| Housing occupied (habitat) | 79%        |
| Secondary housing          | 6%         |
| Vacant                     | 9%         |
| Professional use           | 3%         |

The number of occupied houses in Morocco is 4.582 million houses: this value is officially distributed over 12 regional zones according to (the High Commissariat of the Moroccan Plan) [34].

A conversion of this distribution according to the climatic zones was investigated as presented in Table 7. It is found that this number of houses per climatic zones can be also fragmented into many types such as: modern Moroccan houses which represent the main construction type in Morocco with a percentage of 63%, followed by apartments (25%), villas 4%, traditional Moroccan houses 4%, and finally anarchic construction 4%.

| Zone | Percentage of Houses % | Number of Houses |  |
|------|------------------------|------------------|--|
| 1    | 46                     | 2,109,220        |  |
| 2    | 12.5                   | 572,790          |  |
| 3    | 29.3                   | 1,340,970        |  |
| 4    | 3.1                    | 144,960          |  |
| 5    | 4.1                    | 189,740          |  |
| 6    | 5                      | 224.320          |  |

Table 7. Distribution of occupied houses per climatic zone in Morocco.

These statistics will enable the determination of the thermosyphon's number to be integrated at a national scale.

The study will focus on apartments, modern Moroccan houses, and villas. It should be highlighted that, because of the presence of these variants in the construction sector, it is recommended to consider different capacities related to the type of house for an appropriate analysis. Table 8 presents the system capacity concerning the construction type. The generalization of this system into the building sector will generate an important total investment of 5876.42 million USD. This total investment is found to be 1145.5 million USD, 4144.42 million USD, and 586.50 million USD for modern Moroccan houses (150 L), apartments (200 L), and villas (300 L) respectively.

| Size   | 15      | 0 L                 | 20        | 0 L                 | 300    | ) L                 |
|--------|---------|---------------------|-----------|---------------------|--------|---------------------|
| Zone   | Number  | Area m <sup>2</sup> | Number    | Area m <sup>2</sup> | Number | Area m <sup>2</sup> |
| Zone 1 | 527,400 | 1,160,100           | 1,413,200 | 3,109,000           | 84,400 | 371,300             |
| Zone 2 | 143,200 | 315,100             | 3,837,800 | 844,300             | 23,000 | 100,800             |
| Zone 3 | 335,300 | 737,600             | 898,500   | 1,976,600           | 53,700 | 236,000             |
| Zone 4 | 36,300  | 79,800              | 97,200    | 213,700             | 5800   | 25,600              |
| Zone 5 | 47,500  | 104,400             | 127,200   | 279,700             | 7600   | 33,400              |
| Zone 6 | 56,000  | 123,400             | 150,300   | 330,700             | 8900   | 39,500              |

Table 8. The number of thermosyphon solar water heaters (TSWH) to be installed.

#### 6.3. Total Annual Gains

The total gains or the life cycle savings of the thermosyphon generalization in Morocco by using the subsidies and non-subsidies gas butane prices is presented in Figure 7. This indicator represents the global cost savings resulting from the integration of the thermosyphon system instead of buying gas butane cylinders.

It is concluded, from the comparison of these two scenarios, that, obviously, the gains generated considering subsidies are less than the second case for the six zones. In fact, the government subsidies (on fuels) policy is representing a barrier towards development solar energy projects in Morocco. Moreover, the first zone represents the most important gains by 197.11 million USD in the first scenario against only 44.32 million USD in the second zone. This difference can be explained by the highest solar fraction (68.8%), together with the high intensity of the population concentration with a percentage of 46%. In the zone represented by Agadir, this optimal combination of solar fraction and the number of homes for the first climatic zone gives optimized results and very encouraging gains as it is previously represented. This value becomes significant and would reach 448 million USD per year by canceling government grants.

The third zone is holding the second place with total gains of 69.34 million USD per year. It can be improved by removing the state subsidies to reach 214.63 million USD per year. The other climatic zones achieve lower gains than the previous ones, despite their significant solar fractions which reach 66% (Errachidia) representing the most favorable climate conditions for the system. This result is explained by the minimal percentage of houses.

The energy gains generated by the generalization of thermosyphon systems are presented in Figure 14b. The first zone achieve an energy annual gain of 5943.46 GWh per year, which is distributed according to the different studied configurations: apartment with 1214.60 GWh per year, modern Moroccan houses by 4340.19 GWh annually, and 388.67 GWh generated for the villas type. The integration of solar water heaters in the modern Moroccan houses generates the maximum gains in the six climate zones compared to other types due to the remarkable presence of this type in the typological distribution of housing in the Moroccan territory. In fact, it represents 63% of the total occupied houses, followed by the buildings and finally villas.

Figure 15a–c present the evolution of the annual gains in an interval of 12 years, and under the condition of (non-subsidies) for several type of houses treated in this paper.

The payback period for the proposed sizes and under the six climatic data condition can be determined based on Figure 14. The return on investment (ROI) varies between 3 and 6 years according to the performances of the system related to the meteorological context, the investment and the gains generated which are related also to the performance and the total expenditures produced by the traditional gas butane system. In general, after a period of 6 years the thermosyphons installed in the climatic zones will cover the initial investment and in general they will enable 100% of the life cycle savings.



Figure 14. (a) Total annual gains (with state subsidies). (b) Total annual gains (without state subsidies).



**Figure 15.** (a) Cumulative gains for buildings (non-subsidies scenario). (b) Cumulative gains for modern Moroccan houses (non-subsidies scenario). (c) Cumulative gains for villas (non-subsidies scenario).

Global Results: Cumulative Gains for Different House's Types

The overall average solar fraction presents a national value which is estimated at 62%. Table 9 presents the total gains for different type of house according to the two scenarios (with and without subsidies): the generalization of solar water heaters have an important role to play in the achievement of the development program's goals of the Moroccan market for solar water heaters by (PROMASOL).

This program aims to provide the evolution continuity of thermosyphon installed capacity since 2000 obtained by the analysis of imports conducted by the (AMEE) which is a result presented in Figure 16. This figure is presenting the cumulative area of the SWH installed in Morocco since 2000 to the expectations desired to achieve.

| Type of House   | Apartments                        | Modern and Traditional<br>Moroccan Houses | Villas                          |
|---|-----------------------------------|---|---------------------------------|
| Total Investment  | 1145.5                            | 4144.42                                   | 586.4                           |
|   | Subsidies                         |   |                                 |
| Annual expenditure of gas Water heater (USD)<br>Gains (USD)   | 115.47<br>71.59                   | 3009.45<br>1865.86                        | 36.95<br>22.91                  |
|   | No subsidies                      |   |                                 |
| Annual expenditure of gas Water heater (USD)<br>Gains (USD)<br>The annual gains (the number of gas bottles) | 357.40<br>221.59<br>17.05 million | 957.83<br>593.86<br>45.68 million         | 114.36<br>70.90<br>5.46 million |

**Table 9.** The total gains for different type of houses according to the two scenarios (with and without subsidies).



Figure 16. Cumulative area of the SWH installed in Morocco since 2000 and expectations.

#### 6.4. Environmental Assessment

Using solar water heaters will also make it possible, in contrast to the conventional water heater, to reduce emissions of greenhouse gases. It should be recalled that recently, Morocco announced its engagement to reduce 13% of these gases by 2030, and ratified the Kyoto Protocol, which entered into force in 2005 Table 10 presents the annual  $CO_2$  emissions avoided by the integration and the generalization of the TSWH.

| Zone   | Gains (Number of Gas<br>Cylinder) (million) | Gains (million m <sup>3</sup> of<br>Butane Gas) | CO <sub>2</sub> Emissions<br>Avoided (tones/year) |
|--------|---|---|---|
| Zone1  | 44,610.75                                   | 220,377   | 1,856,000   |
| Zone 2 | 8.36  | 41.29   | 446,900   |
| Zone 3 | 16.51                                       | 81.56   | 891,800   |
| Zone 4 | 1.59  | 7.86  | 85,300  |
| Zone 5 | 3.1   | 14.83   | 160,200   |
| Zone 6 | 3.56  | 1.756   | 203,700   |

**Table 10.** The annual  $CO_2$  emissions avoided by the integration and the generalization of the TSWH.

The maximum  $CO_2$  emissions avoided are remarkably visualized on the first climatic zone which presents the highest number of houses, and as a result the highest number of SWH installed, and energy savings.

The calculation of the  $CO_2$  emissions avoided is made based on the quantity of the butane gas consumed in the conventional system; this consumption of the butane gas will be eliminated by implementing the generalization project. This step required adopting the butane gas characteristics where it generates 230 g of  $CO_2$  emissions for each kWh produced. Furthermore, for bottles of 6 kg, the discharges correspond to 157 tons of  $CO_2$  equivalent. The bottles of 10 kg, under the same conditions, give 160 kg of  $CO_2$  equivalent. They finally amount to a bottle of 13 kg to 150 kg of  $CO_2$  equivalent.

# 7. SWH Generalization a Bridge Idea to a Promoter Economic Project (Manufacturing Moroccan SWH)

Nowadays, the global perspective focuses on the economy, the human, energy, and the environment, achieving optimum energy consumption and reducing greenhouse gas emissions. Besides, with this 2020 pandemic, the economic sector's growth has become more urgent than before.

In Morocco, the project of this paper can be realized currently only by the import of this technology; this requires reflection to a local production unit of solar water heaters. Here, the idea of an innovative project was born (SOL'R SHEMSY project). We are working through the development of a Moroccan solar water heater ready to be industrialized locally. Hence, the project integrates all these goals and offers a balanced solution; technology, economy, and social and environment.

The local production will present solar water heaters with affordable prices adapted to the social context, breaking the most significant barrier of this technology's extensive integration, which is the high prices resulting from the importation effect.

The manufacturing project will bring various high-quality products intended for multiple customer categories to meet all social and industrial clients' needs, presenting the high technology with the best efficiencies, yields, and reasonable prices adapted to the Moroccan purchasing power. In particular, the main obstacle to its adoption is the high-security and weak support of African states. In economic and social terms, this project will create permanent jobs and achieve significant energy gains by reducing the energy bills costs for a range of sectors: housing sector, hotels, hospitals, schools and universities, sports sector (heated swimming water), industrial and agricultural sector. Strengthening the economic Moroccan–African industry through the manufacturing and marketing of solar water heaters and why not export. Finally, generalizing the use of these products would significantly reduce carbon dioxide emissions and combat the dangers of the gas heaters that kill dozens a year.

#### 8. Conclusions

In this paper the thermosyphon solar water heater was presented, modeled, simulated and assessed according to six Moroccan climatic zones which represent the recent zoning carried out by the Moroccan Agency of Energy Efficiency (AMEE), in order to predict the system performances, and the dynamic behaviors of different parameters which are describing the thermosyphon. The system was modeled and simulations where launched under TRNSYS simulation program.

According to the simulation results the thermosyphon's performances in terms of the annual average solar fraction varies between 50% and 70%. The results confirmed that the climatic conditions are the key of the simulation. They have to be taken into consideration to optimize the overall system efficiency. Moreover, an economic study which is about the generalization of this technology was conducted to analyze the potential benefits offered by this solar solution in different zones in Morocco from a weather point of view, and to predict the total life-cycle savings. In fact, life-cycle savings were optimal in the first zone represented by Agadir, due to the optimal combination of performances and high needs that are concentrated in this zone. To complete this study, an environmental section was developed to exhibit the amount of  $CO_2$  emissions that can be avoided by the implantation of this project. The results confirmed that a considerable amount of greenhouse gas emissions is reduced.

The penetration of large-scale solar water heaters in Morocco is prevented by many barriers, such as the understanding's lack among the population of the financial unattractiveness to poor households and the benefits they provide. However, thermosyphon will be accepted easier when the population understands all these technology advantages. In the case of SWH systems, the benefits are not immediately visible for a payback period of six years: the energy bill will be reduced, but not fast enough in order to justify the cost of installation. Thus, the governmental subsidies will be an important incentive solution for beneficiaries. The generalization of this type of installation will not be possible without the introduction of incentive mechanisms that involves the public authorities, subsidizing the purchase of solar water heaters which will enable citizens to equip themselves at a lower cost.

The advantages linked to the generalization of the thermosyphon in Morocco are multiple, both economically and environmentally. Citizens could save their energy bill in the long term, since after an average of six years they would have profitable purchase price. Moreover, manufacturing the solar water heater in Morocco will lower the import bill cost. Furthermore, it will also help the development of subcontracting and involve SMEs (Small and Medium Enterprises) in the manufacture of this product. Hence, entrepreneurship in this solar field will grow and be encouraged. Therefore, jobs will be created which will absorb unemployment.

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#### Nomenclature

| Ac                  | Collector area (m <sup>2</sup> ).                                     |
|---------------------|---|
| F <sub>R</sub>      | Collector heat removal efficiency factor (-).                         |
| $F_R U_L$           | Slope of the collector efficiency curve (kJ $h^{-1} K^{-1} m^{-2}$ ). |
| $F_{R(\tau\alpha)}$ | Intercept efficiency corrected for non-normal incidence (-).          |
| F                   | Friction factor (-).  |
| F′                  | Collector efficiency factor (-).                                      |
| UL                  | Heat loss coefficient (kJ $h^{-1} K^{-1} m^{-2}$ ).                   |
| G <sub>test</sub>   | Collector mass flux at test conditions (kg $h^{-1} m^{-2}$ ).         |

- G Collector flow rate per unit area (kg  $h^{-1} m^{-2}$ ).
- $\rho_i$  Density of ith node (kg m<sup>-3</sup>).
- $\Delta h_i$  Height of the ith node (mm).
- $\Delta P_i$  Change in pressure across the ith node (bar).
- $h_{Li}$  Frictional head loss in the ith node on the pipe (-).
- H<sub>p</sub> The friction head losses on the pipes (-).
- r Ratio of collector heat removal efficiency factor, F<sub>R</sub>, to the test conditions (-).
- N<sub>x</sub> Number of equal sized collector nodes (-).
- K Correction coefficient for additional friction due to developing flow in the pipe (-).
- k Node number (-).
- Re Reynolds coefficient (-).
- f Friction factor for flow in pipes (-).
- v Velocity of the fluid (m  $s^{-1}$ ).
- $\dot{m}$  Thermo siphon flow rate (kg h<sup>-1</sup>).
- $C_p$  Specific heat of working fluid (kJ kg<sup>-1</sup> °C<sup>-1</sup>).
- g Gravitational constant (N  $m^2 kg^{-2}$ ).
- $(\tau \alpha)$  Product of the cover transmittance and the absorber absorptance (-).
- $(\tau \alpha)_b$   $(\tau \alpha)$  for beam radiation depends on the incidence angle (-).
- $(\tau \alpha)_n$   $(\tau \alpha)$  at normal incidence (-).
- $(\tau \alpha)_s$   $(\tau \alpha)$  for sky diffuse radiation (-).
- $(\tau \alpha)_g$   $(\tau \alpha)$  for ground reflected radiation (-).
- $I_{bT}$  Beam radiation incident of the solar collector (kJ h<sup>-1</sup> m<sup>-2</sup>).
- $I_d$  Diffuse horizontal radiation (kJ h<sup>-1</sup> m<sup>-2</sup>).
- $I_T$  Global radiation incident on the solar collector (kJ h<sup>-1</sup> m<sup>-2</sup>).
- $I_T$  Total incident radiation per unit area (kJ h-1 m-2).
- $\beta$  Collector slope above the horizontal plane (°).
- $\theta$  Incident angle for beam radiation (°).
- b<sub>0</sub> Negative of the 2nd order coefficient in the IAM curve fit equation (-).
- IAM Incident angle modifier (-).
- $T_a$  Ambient temperature (°C).
- $T_{ci}$  Collector inlet temperature (°C).
- $T_{CO}$  Collector outlet temperature (°C).
- $L_h$  Length of collector headers (mm).
- L<sub>co</sub> Length of collector outlet (mm).
- $L_{ci}$  Length of collector inlet (mm).
- d<sub>i</sub>,d<sub>o</sub> Diameter of collector inlet and outlet pipes (mm).
- $L_i$ ,  $L_0$  Length on inlet and outlet piping (mm).
- H<sub>c</sub> Vertical distance between outlet and inlet of collectors (mm).
- H<sub>O</sub> Vertical distance between outlet of tank and inlet to collector (mm).
- D<sub>r</sub> Riser tank diameter (mm).
- D<sub>h</sub> Header tank diameter (mm).
- V Tank volume (L).
- L Pipe length (mm).
- d Pipe diameter (mm).
- N<sub>c</sub> Number of parallel collector risers (-).
- $U_{api}$  Conductance for heat losses from collector inlet pipe (kJ h<sup>-1</sup> k<sup>-1</sup>).
- $U_{Apo}$  Conductance for heat losses from collector outlet pipe (kJ h<sup>-1</sup> k<sup>-1</sup>).
- $(UA)_s$  Overall UA value for storage tank (kJ h<sup>-1</sup> k<sup>-1</sup>).
- $Q_{aux,max}$  Maximum heating rate (kW).
- P<sub>max</sub> Maximum pressure (bar).
- $K_T$  Thermal losses of the tank ((kJ h<sup>-1</sup> m<sup>-2</sup>).
- C<sub>sc</sub> Capacity of solar circuit (L).
- $E_{coll}$  Efficiency of the collector (%).
- $F_{sol}$  Solar fraction of the system (%).
- $Q_{aux}$  Auxiliary heating load (kJ h<sup>-1</sup>).
- $Q_{DHW}$  Energy rate to load (kJ h<sup>-1</sup>).
- $Q_{ucoll}$  Energy rate from heat source (kJ h<sup>-1</sup>).
- $I_{coll}$  Total radiation on tilted surface (kJ h<sup>-1</sup> m<sup>-2</sup>).
- ROI Return on investment (years).

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